Probing beyond the Standard Model:

The neutron EDM experiment at PSI

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KU Leuven

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Speaking on behalf of the nEDM collaboration

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  - Baryon asymmetry
  - Probing beyond the Standard Model
- Experimental method & setup
- Current status
  - Statistical sensitivity
  - Systematic effects
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- Conclusion

Motivation - Baryon asymmetry

- Why is there so much more matter than antimatter in the universe? Baryon asymmetry parameter:

Observed: $$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

Standard Model prediction: $\sim 10^{-18}$

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- Conditions for baryon asymmetry by Sakharov[1]:
    - Baryon number violation
    - C and CP violation
    - Departure from local equilibrium

[1] JETP Lett 5, 24-27 (1967).

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  - C and $\boxed{\text{CP violation}}$
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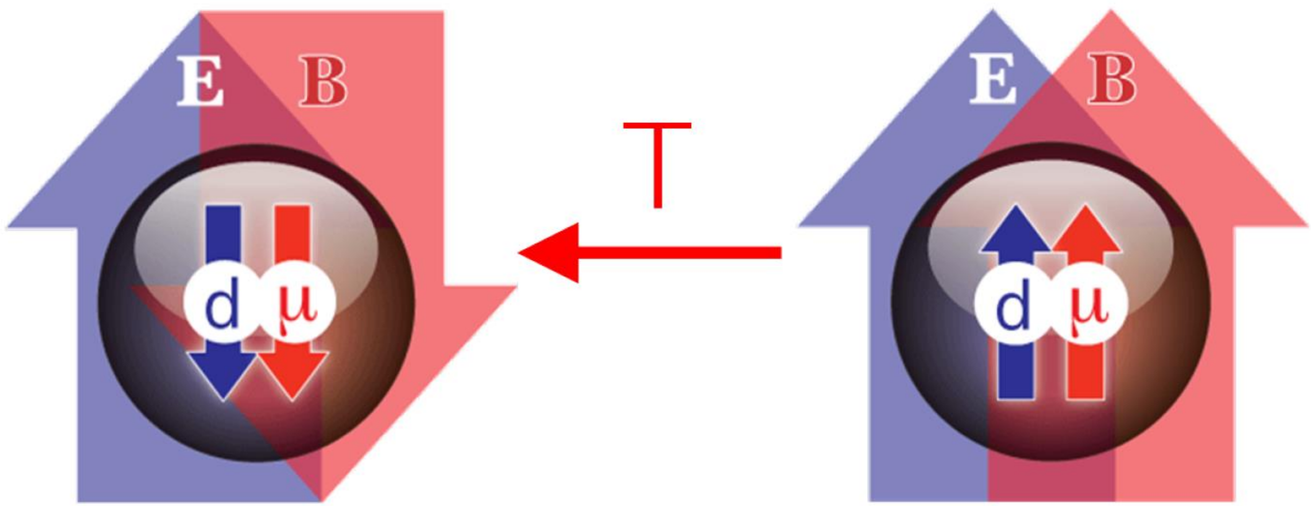
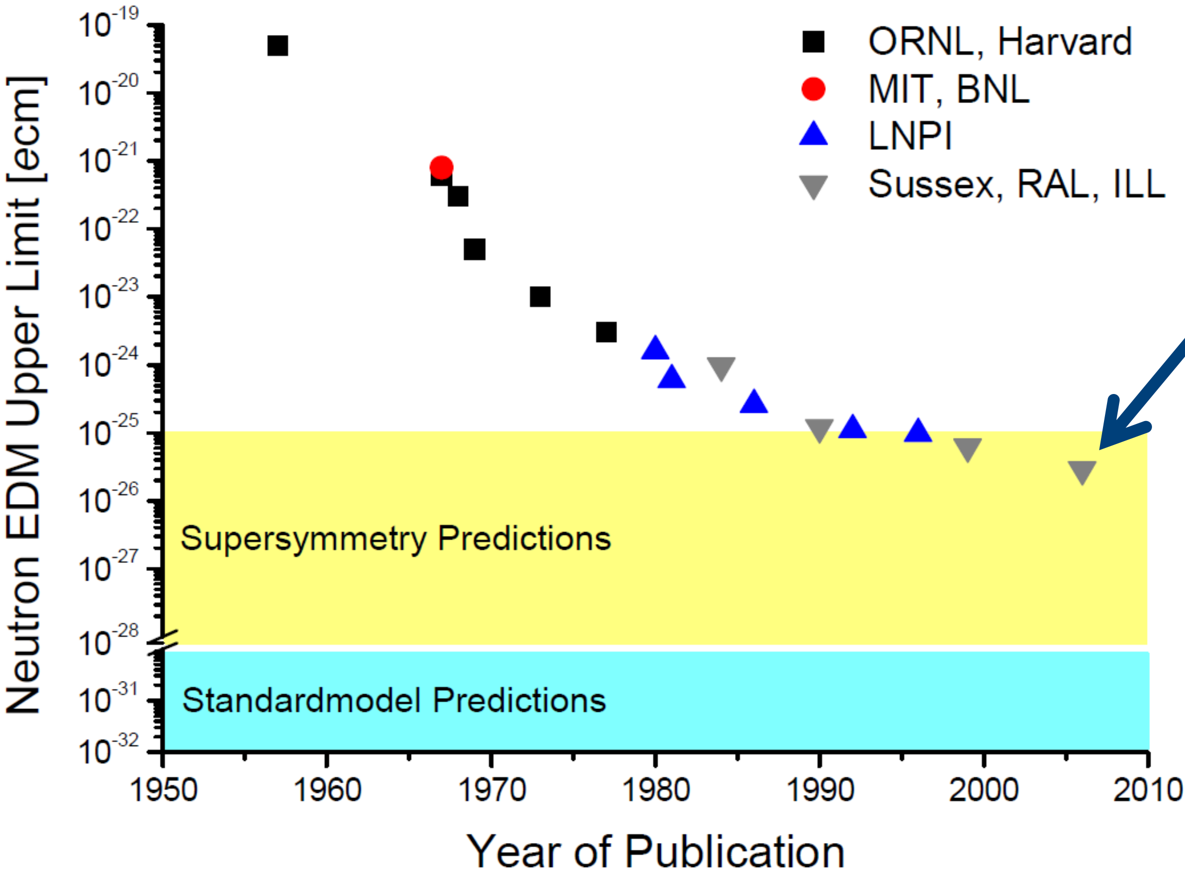
Motivation - CP violation

Permanent Electric Dipole Moment (EDM) of a particle violates CP symmetry



$$\mathrm{T}\mathcal{H} = -d\frac{-\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|}\boldsymbol{E} - \mu\frac{-\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|}(-\boldsymbol{B}) \qquad \mathcal{H} = -d\frac{\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|}\boldsymbol{E} - \mu\frac{\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|}\boldsymbol{B}$$

Motivation - Constrain non-SM physics



Best limit (2006)[2]:

$$d_n < 2.9 \times 10^{-26} \;\; e \cdot \mathrm{cm}$$
$$(90\% \text{ C.L.})$$

Standard Model prediction:

$$d_n \approx 10^{-32} \ldots 10^{-30} \;\; e \cdot \mathrm{cm}$$

(without QCD θ-term)

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[2] Baker et al., PRL 97 (2006) 131801.

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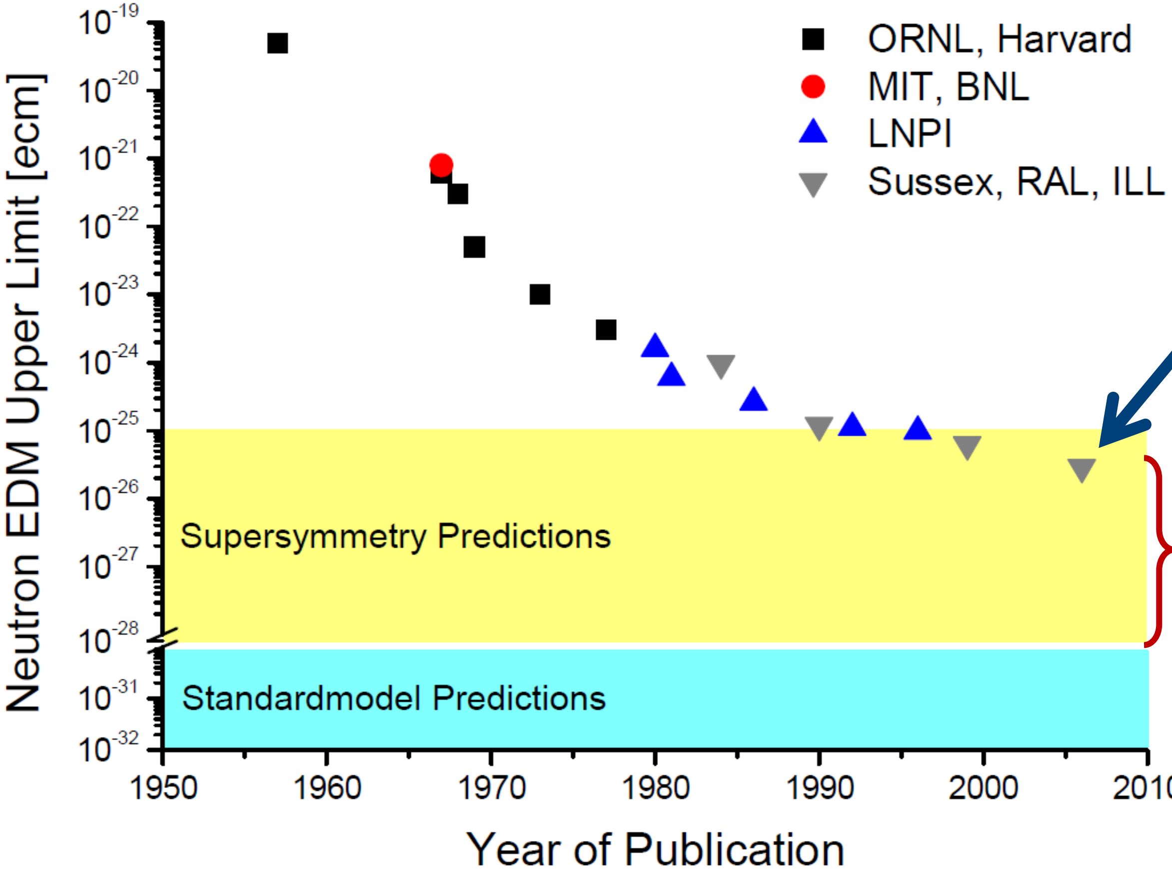

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Excellent observable to constrain non-SM physics!

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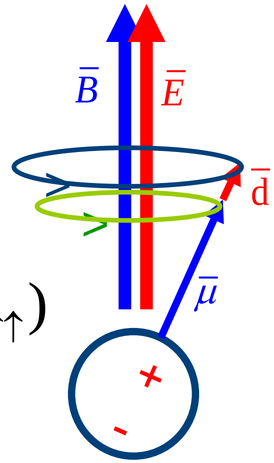
Experimental method

Ramsey's method of separated oscillatory fields:

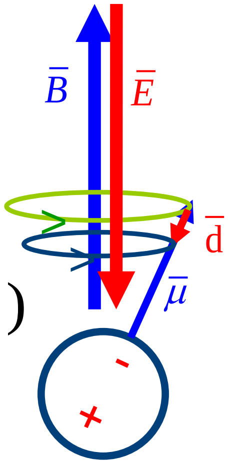
1. Measure Larmor precession frequency with parallel E and B

$$\hbar\omega_{\uparrow\uparrow} = 2(\mu_n B_{\uparrow\uparrow} + d_n E_{\uparrow\uparrow})$$



2. Measure Larmor precession frequency with antiparallel E and B

$$\hbar\omega_{\uparrow\downarrow} = 2(\mu_n B_{\uparrow\downarrow} - d_n E_{\uparrow\downarrow})$$



3. Take the difference!

$$d_n = \frac{\hbar\Delta\omega - 2\mu_n(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})}{2(E_{\uparrow\uparrow}+E_{\uparrow\downarrow})} = \frac{\hbar\Delta\omega}{4|E|}$$

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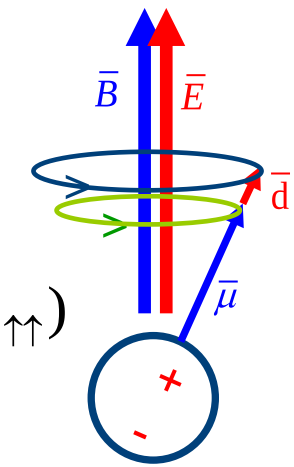

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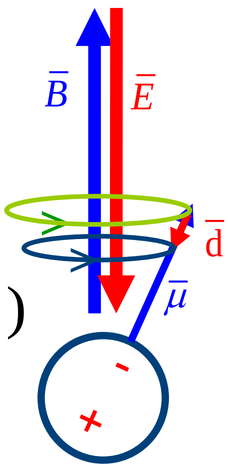

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$$d_n = \frac{\hbar\Delta\omega - 2\mu_n \boxed{(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})}}{2(E_{\uparrow\uparrow} + E_{\uparrow\downarrow})} =$$

Knowledge of magnetic field is important!!!

Experimental method

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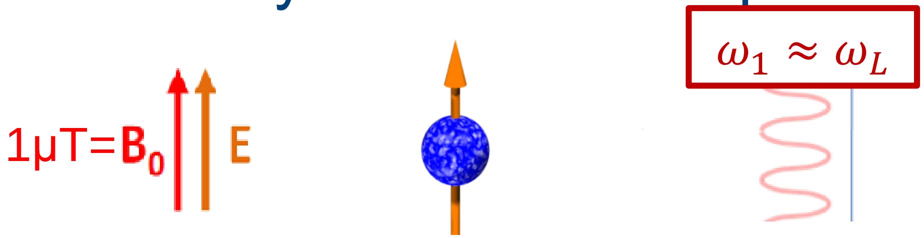

1. Polarize neutrons in direction of B_0. Choose frequency ω_1 of external clock.

Experimental method

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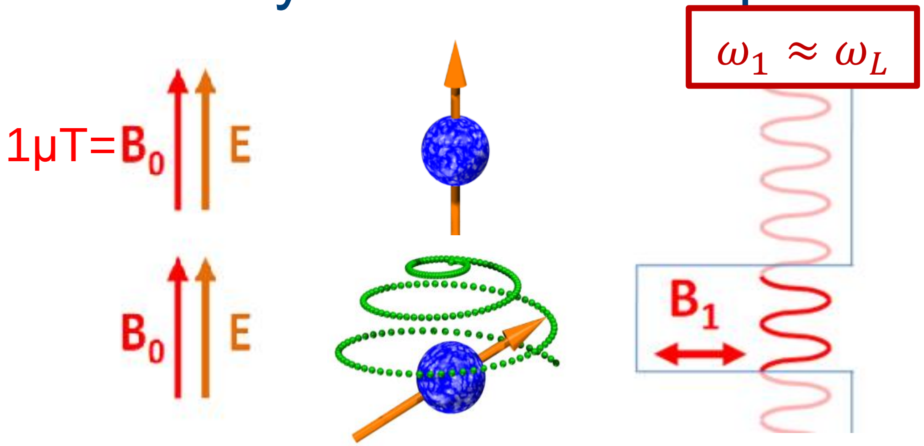

1. Polarize neutrons in direction of B_0. Choose frequency ω_1 of external clock.

2. Apply rotating (ω_1) magnetic field B_1 perpendicular to B_0 for 2s. Neutron spin is flipped.

Experimental method

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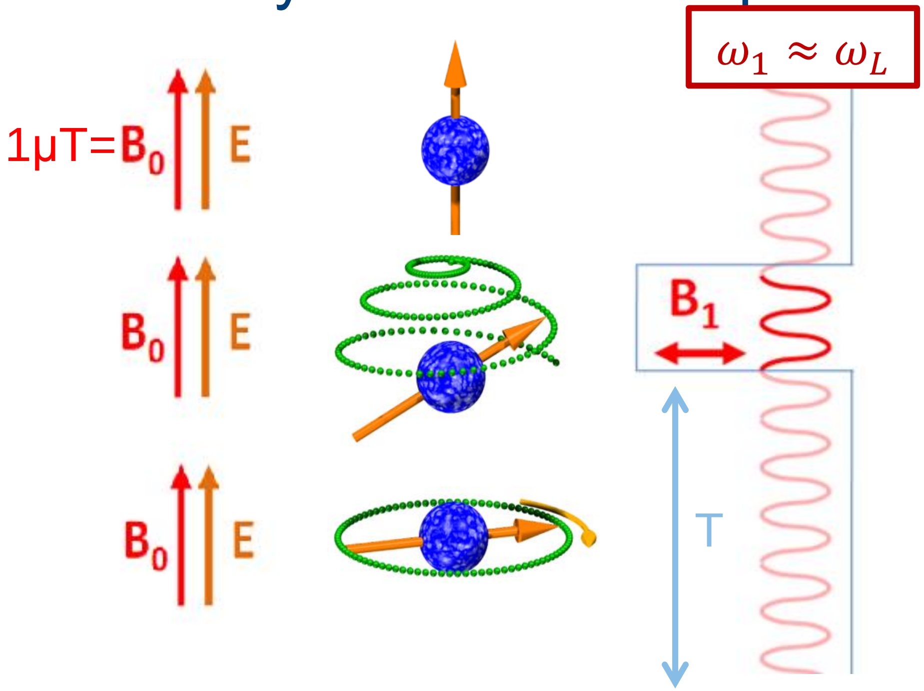

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3. Neutrons precess freely during T (typically 180s).

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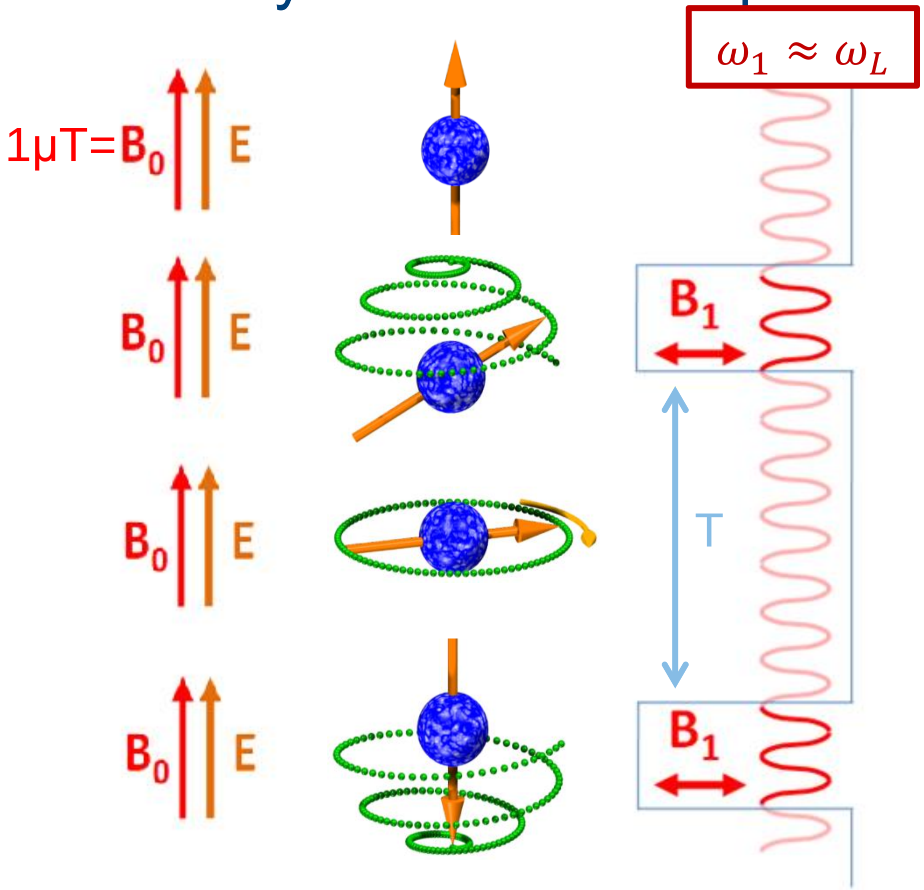

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4. Second spin flip pulse in phase with first one. Neutron spin is flipped again.

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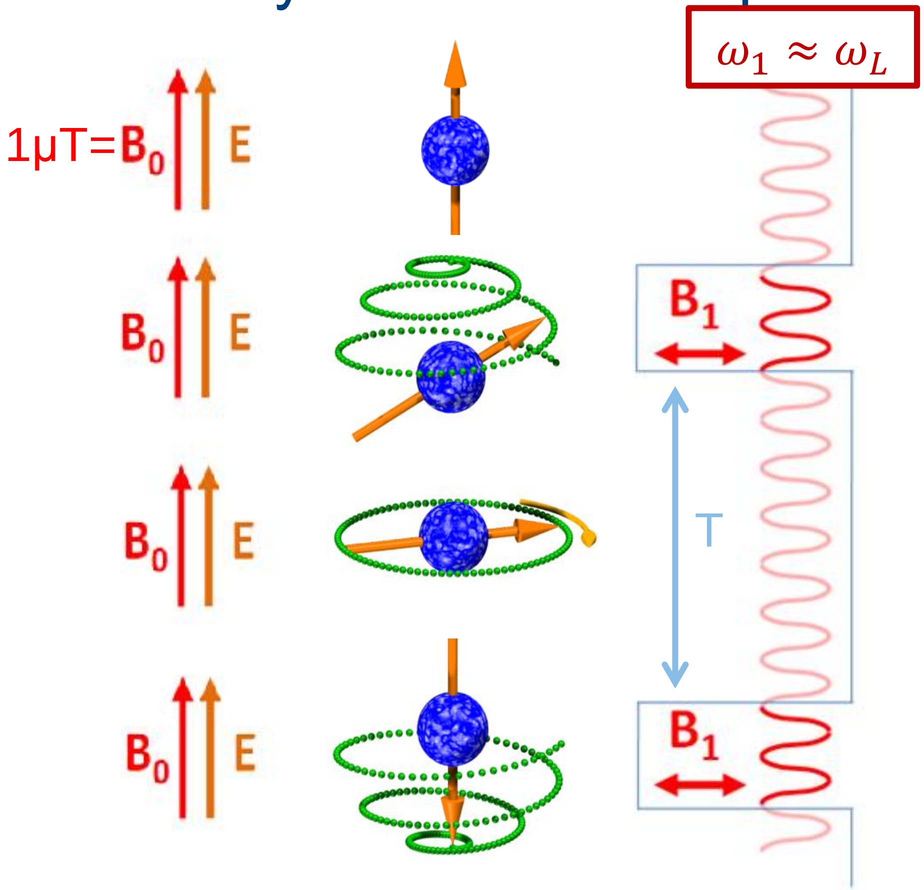

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5. Count spin up/down neutrons in function of ω_1

Experimental method

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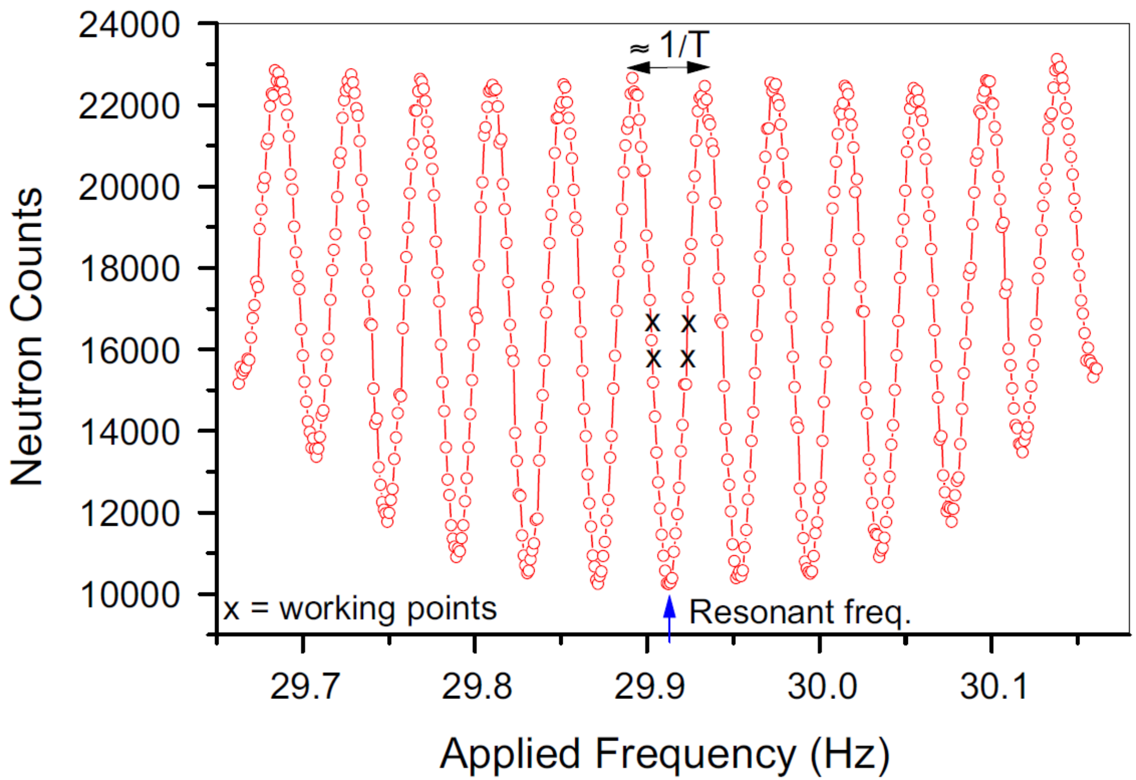

B=1μT

Uncertainty on d_n due to counting statistics:

$$\sigma_{d_n} = \frac{\hbar}{2E\alpha T\sqrt{N}}$$

E: electric field
α: visibility (polarization)
T: free precession time
N: neutron counts

Setup

About 45 people in the nEDM collaboration, 7 countries

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Setup

Located at the Paul Scherrer Institute

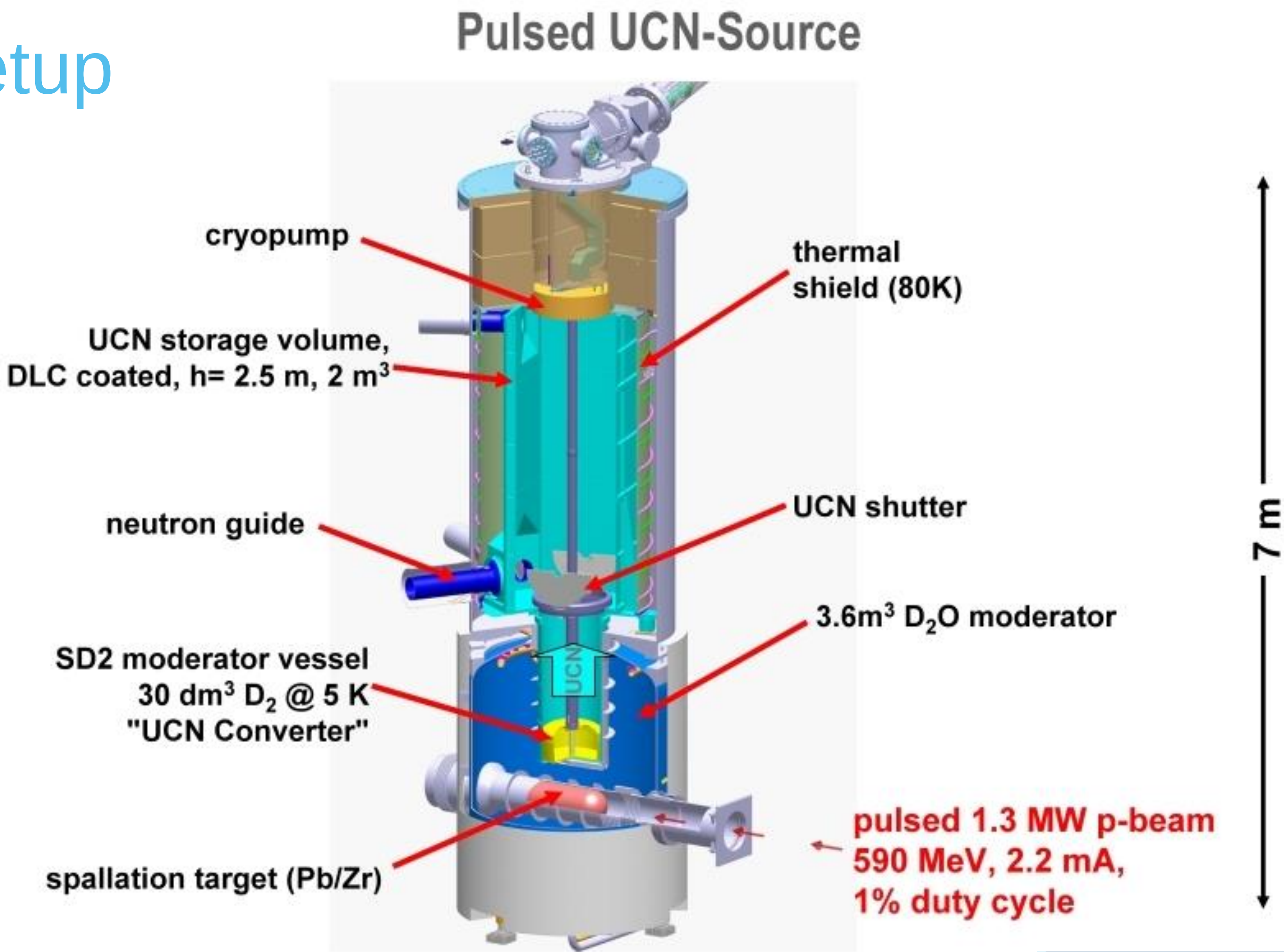
Setup

Ultra cold neutrons

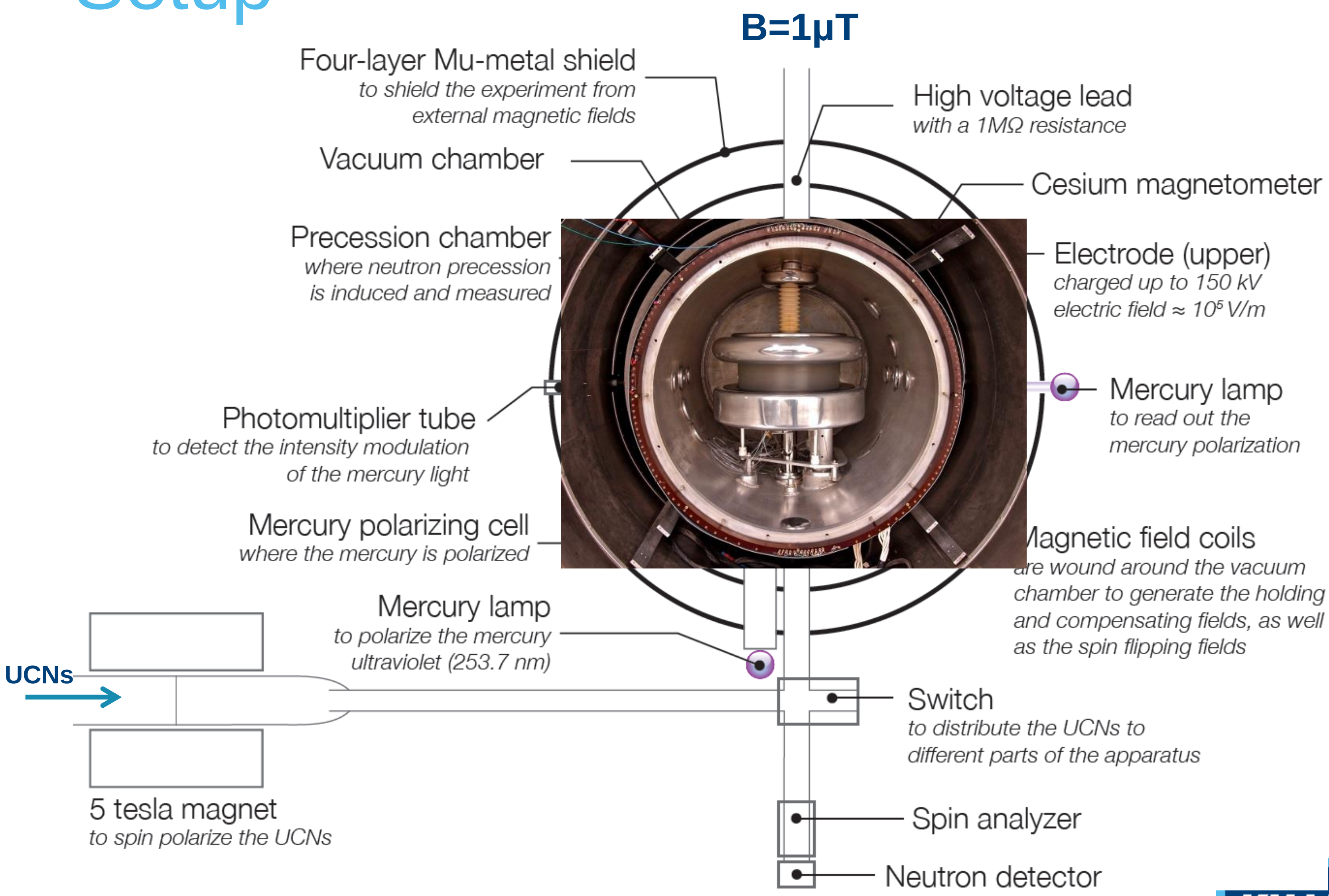
- UCNs have very low energies: ~100neV
- Speed less than 7m/s
- Full reflection at certain surfaces
- Can be guided and stored in a vessel!

Setup was moved from ILL to PSI where a dedicated UCN source has been built.

Setup


Pulsed UCN-Source
cryopump
thermal shield (80K)
UCN storage volume, DLC coated, h= 2.5 m, 2 m³
neutron guide
UCN shutter
3.6m³ D₂O moderator
SD2 moderator vessel 30 dm³ D₂ @ 5 K "UCN Converter"
UCN
spallation target (Pb/Zr)
pulsed 1.3 MW p-beam 590 MeV, 2.2 mA, 1% duty cycle
7 m

Setup



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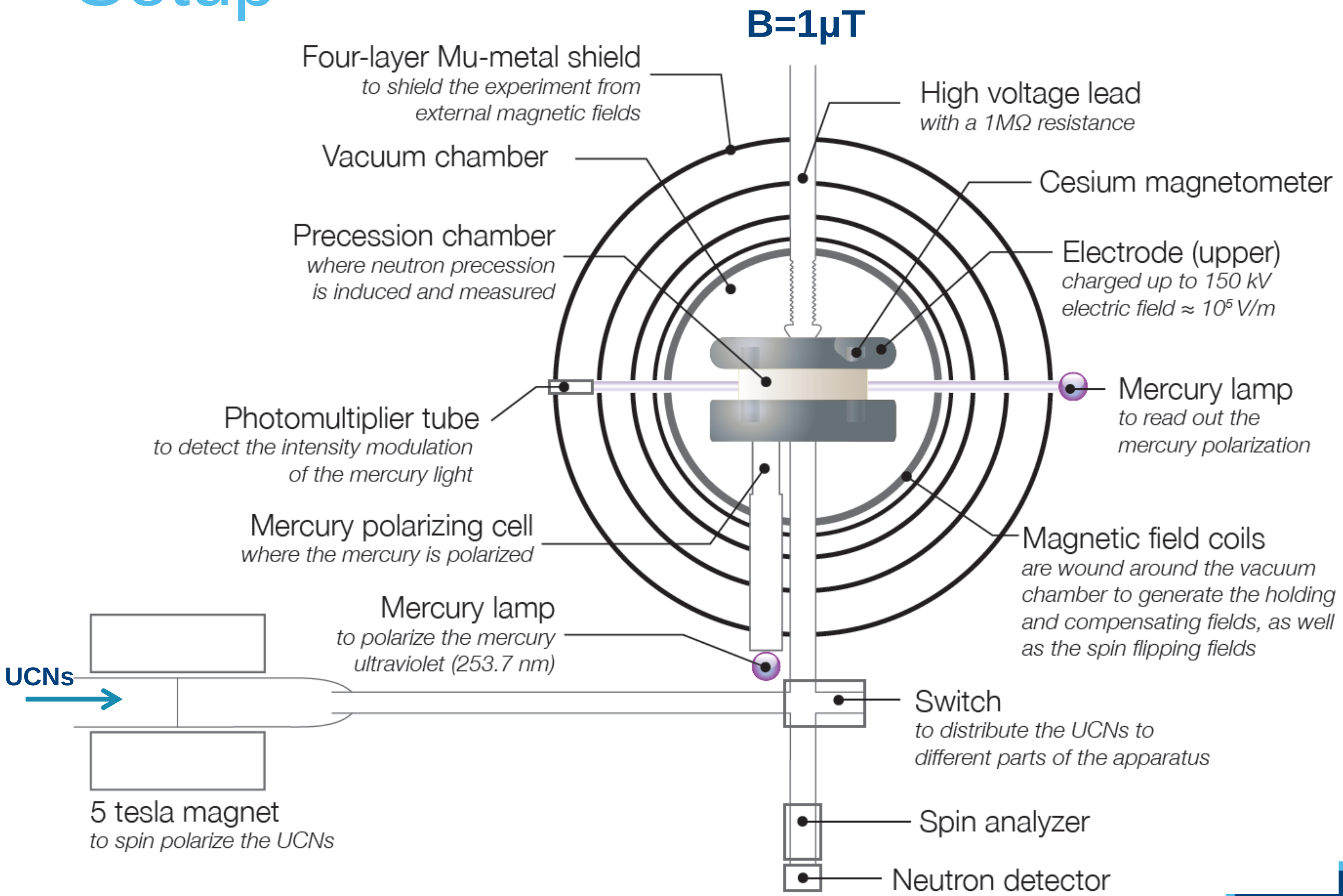
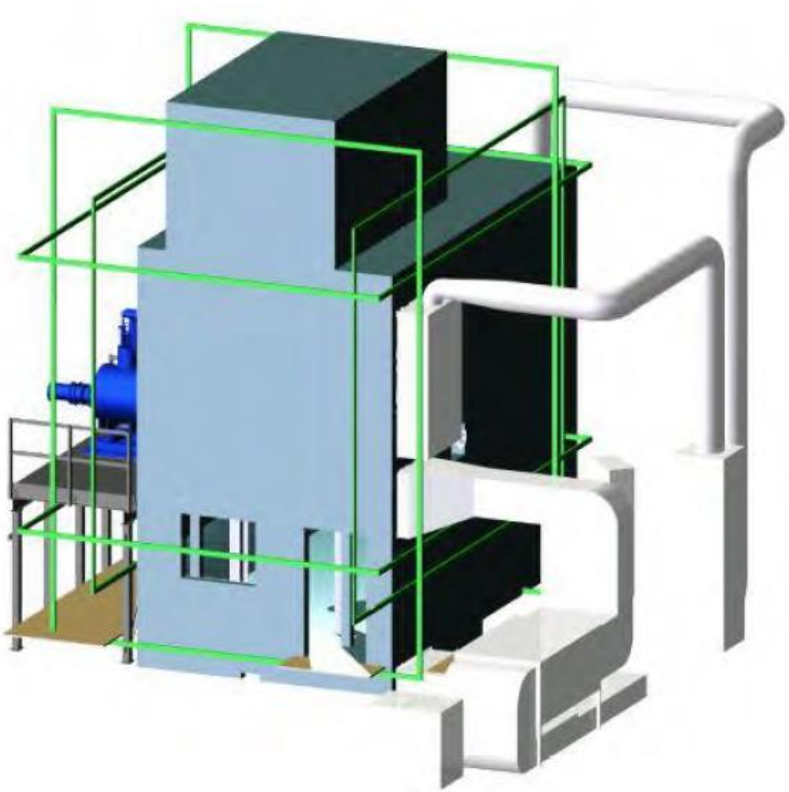
Setup

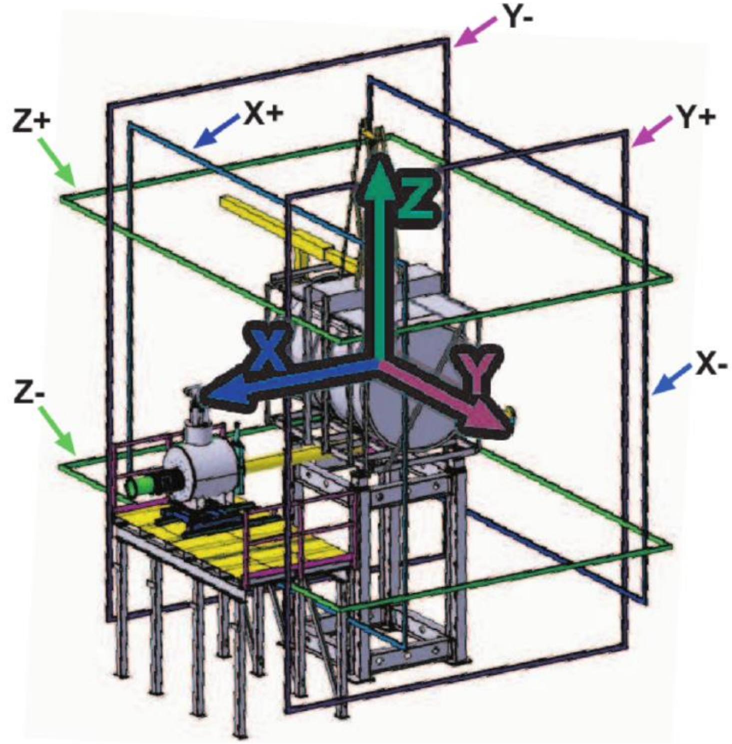


B=1μT
Four-layer Mu-metal shield
to shield the experiment from external magnetic fields
Vacuum chamber
Precession chamber
where neutron precession is induced and measured
Photomultiplier tube
to detect the intensity modulation of the mercury light
Mercury polarizing cell
where the mercury is polarized
Mercury lamp
to polarize the mercury ultraviolet (253.7 nm)
UCNs
5 tesla magnet
to spin polarize the UCNs
High voltage lead
with a 1MΩ resistance
Cesium magnetometer
Electrode (upper)
charged up to 150 kV
electric field ≈ 10⁵ V/m
Mercury lamp
to read out the mercury polarization
Magnetic field coils
are wound around the vacuum chamber to generate the holding and compensating fields, as well as the spin flipping fields
Switch
to distribute the UCNs to different parts of the apparatus
Spin analyzer
Neutron detector

Setup

Surrounding field compensation and temperature stabilisation





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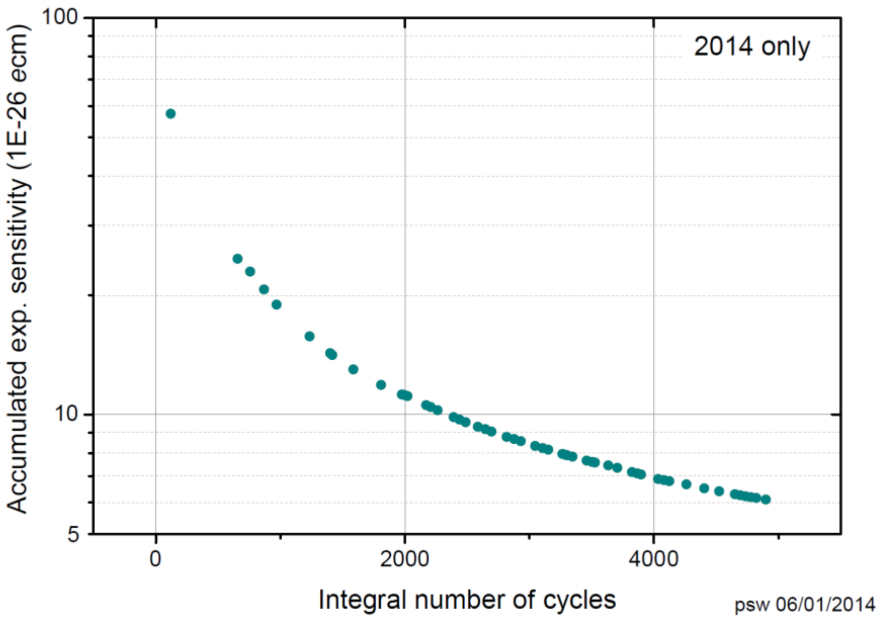
Statistical sensitivity

Statistical uncertainty: $\sigma(d_n) = \dfrac{\hbar}{2\alpha E T \sqrt{N}}$



20 days in 2014:
accumulated 6E-26 ecm

2015 data taking ongoing:
<2E-25ecm/day

We should reach 1.5E-26ecm in 2016

Systematic effects

Knowledge of magnetic field is important:

$$d_n = \frac{\hbar\Delta\omega - 2\mu_n \boxed{(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})}}{2(E_{\uparrow\uparrow} + E_{\uparrow\downarrow})}$$

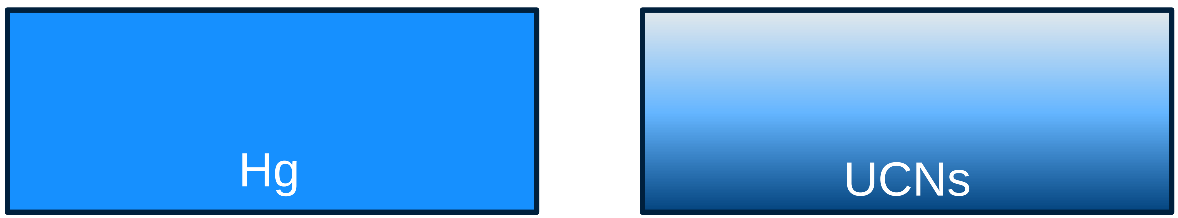
We have a cohabiting Hg magnetometer to monitor drifts

- Gas of polarised 199Hg inside precession chamber
- RF pulse to flip the spin 90 degrees
- Measure absorption of circularly polarised light which is spin-dependent
- Modulation frequency of absorption is Larmor frequency

Systematic effects

Effects related to the Hg magnetometer:

1. Gas at room temperature, so density distribution is different compared to UCNs. If there is a vertical gradient the two species see a different field.



2. Geometric phase effect: interplay of motional magnetic field (vxE) and magnetic field gradients
3. Hg atoms sample the field non-adiabatically $\|\langle\vec{B}\rangle\|$, whereas neutrons are adiabatic $\langle\|\vec{B}\|\rangle$

Crossing point analysis (RAL-Sussex) to take these effects into account

Systematic effects

Crossing point analysis:

1. Shift of center of gravity:

$$R = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \pm \frac{h}{|B|} \frac{\partial B_z}{\partial z} \right)$$ for B_0 up/down

2. Interplay of the motional magnetic field with magnetic field gradients gives rise to a frequency shift proportional with the electric field:

$$\Delta f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}}^2 D^2}{32\pi c^2} \frac{\partial B_z}{\partial z} E$$

which translates into a false nEDM:

$$d^{\mathrm{false}} = \frac{\partial B_z}{\partial z} 1.150 \times 10^{-27} e \cdot \mathrm{cm}/(\mathrm{pT}/\mathrm{cm})$$

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Systematic effects

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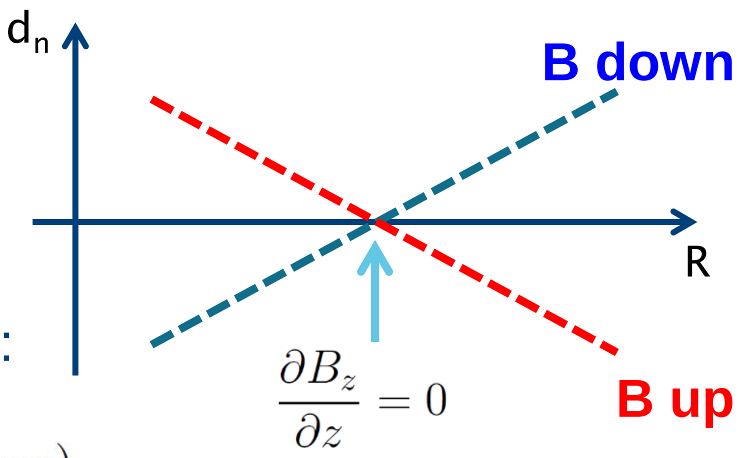

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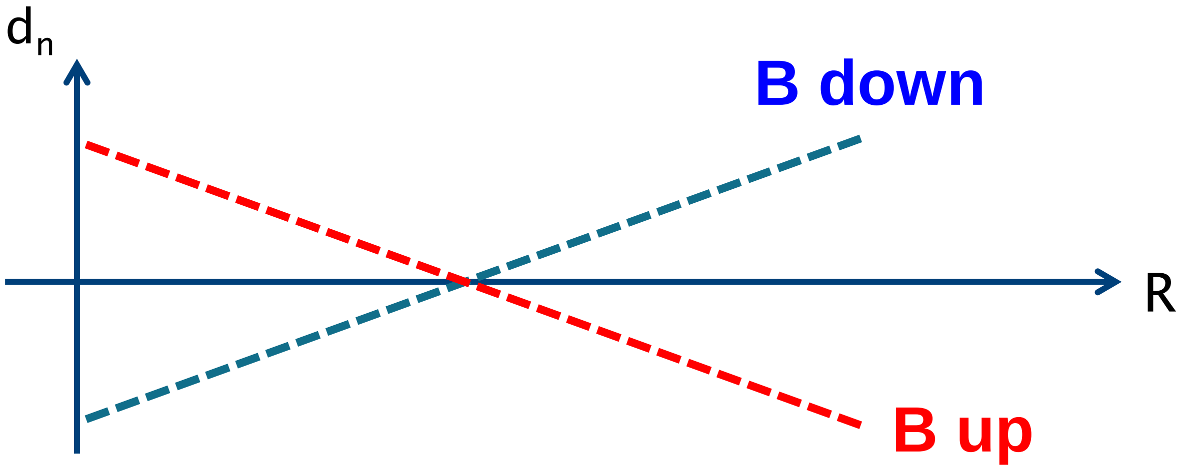

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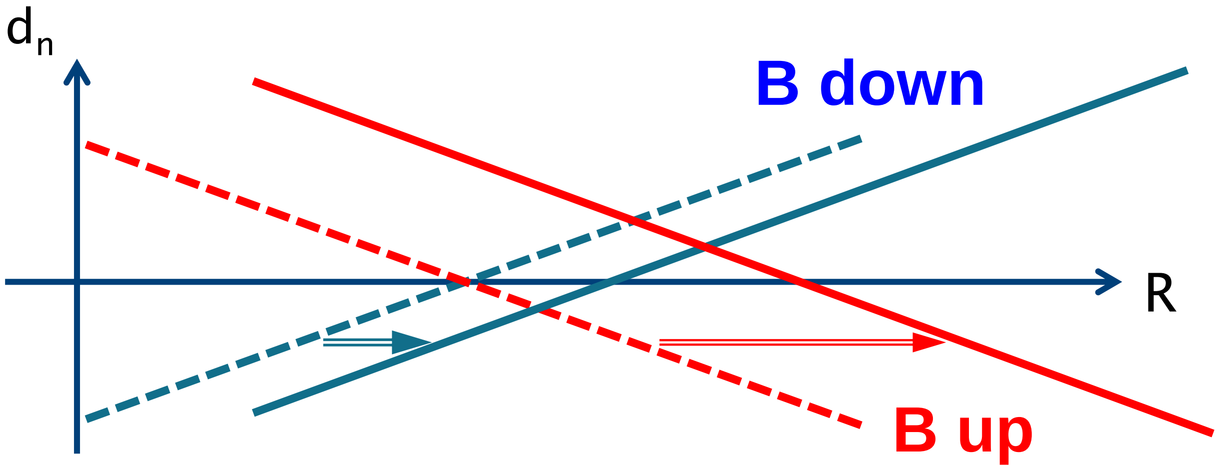

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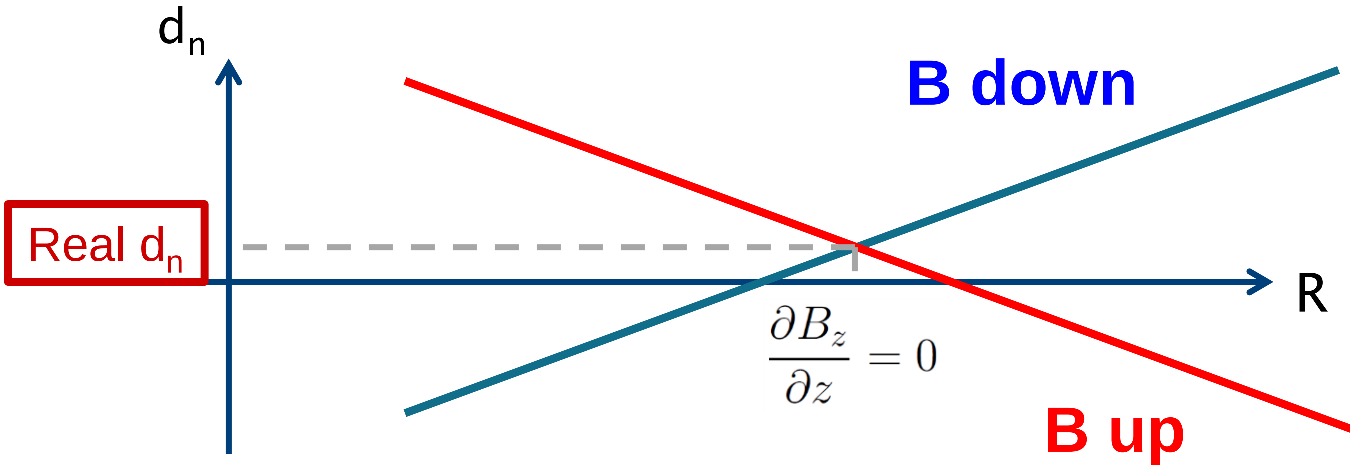

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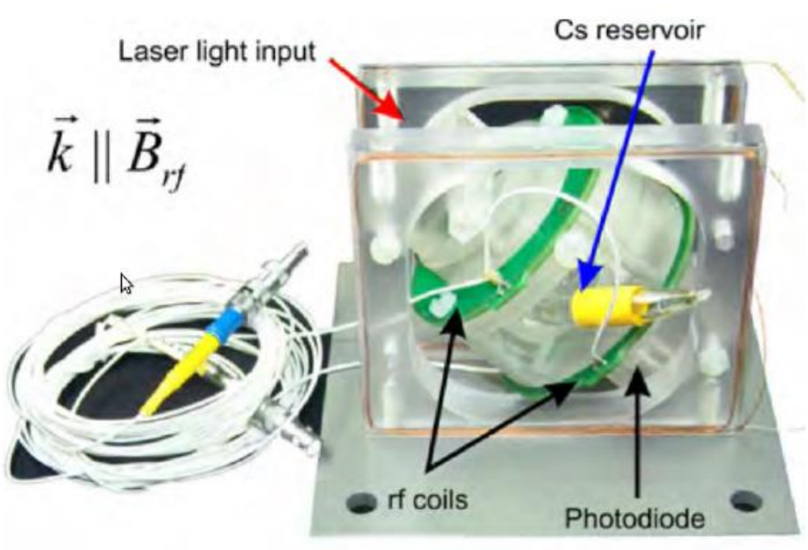
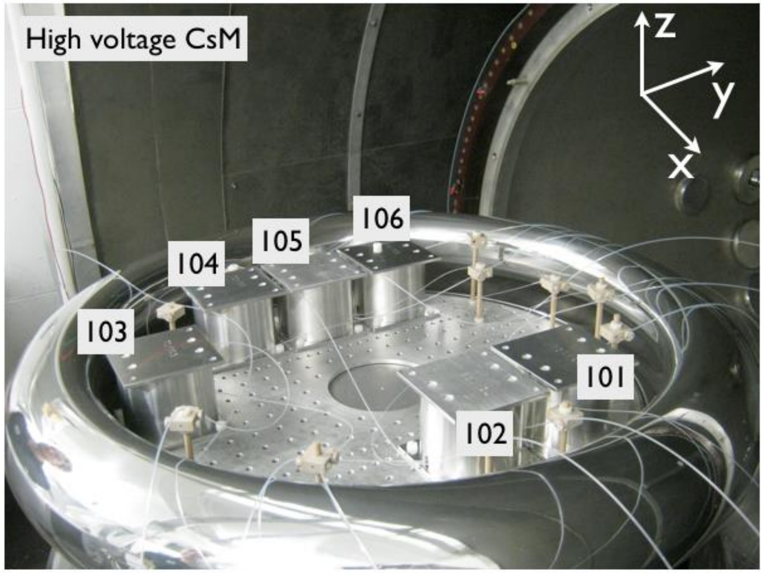
Two options:
-Calculate from field maps
-Monitor online with Cs magnetometers
(still in development!)

Systematic effects

Cs magnetometers give information about the field shape:

- 16 CsM around the precession chamber
- Probe the magnitude of the field locally





Systematic effects

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Variometer method to measure transverse components:

- Apply extra transverse magnetic field and measure response of CsM

$$||\vec{B}_0 + I\vec{B}_{\mathrm{DC}}||^2 = ||\vec{B}_0||^2 + I\boxed{\vec{B}_0 \cdot \vec{B}_{\mathrm{DC}}} + I^2||\vec{B}_{\mathrm{DC}}||^2$$

- If $\vec{B}_{\mathrm{DC}}$ is known well enough, one can extract B_T

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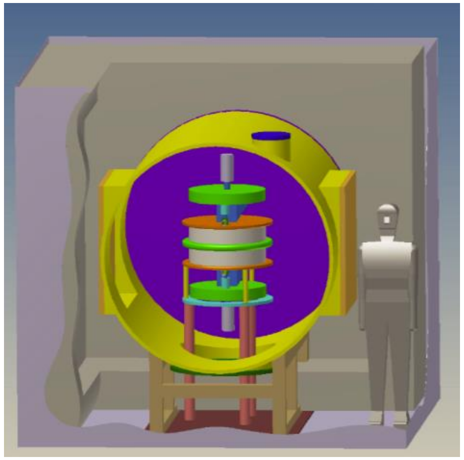
Next phase: n2EDM

Based on experience with nEDM setup, we are building a new improved setup:

- New mu-metal shield
- Double chamber setup
- He magnetometers
- Improved Hg magnetometer (laser readout)
- Vector Cs magnetometers
- Simultaneous spin analysis
- Current source stabilised with KM
- …



Prospect: start data taking in 2018-2019

Goal: $3 \times 10^{-27} e \cdot \mathrm{cm}$

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Conclusion & Outlook

Our apparatus is functioning well:

- Sensitivity is excellent
- Systematic effect are under control $< 5 \times 10^{-27} e \cdot \mathrm{cm}$

We should reach $1.5 \times 10^{-26} e \cdot \mathrm{cm}$ by mid 2016!

Next stage is to build a new setup (n2EDM) which should be able to reach $3 \times 10^{-27} e \cdot \mathrm{cm}$

Thank you for your attention!

Current status - Setup

- Improved version of the RAL-Sussex-ILL apparatus (current best limit) at powerful new UCN source at PSI

- Higher statistical sensitivity
  - Increase UCN lifetime
    - New storage chamber
    - New neutron guides
  - Higher electric field
    - New electrodes
  - More UCNs
    - UCN source
    - New neutron detection system
  - …

- Magnetic field control
    - Cesium Magnetometers
    - Thermal stabilisation
    - Surrounding field compensation
    - Magnetic field mapping
    - Correction coils
    - ...

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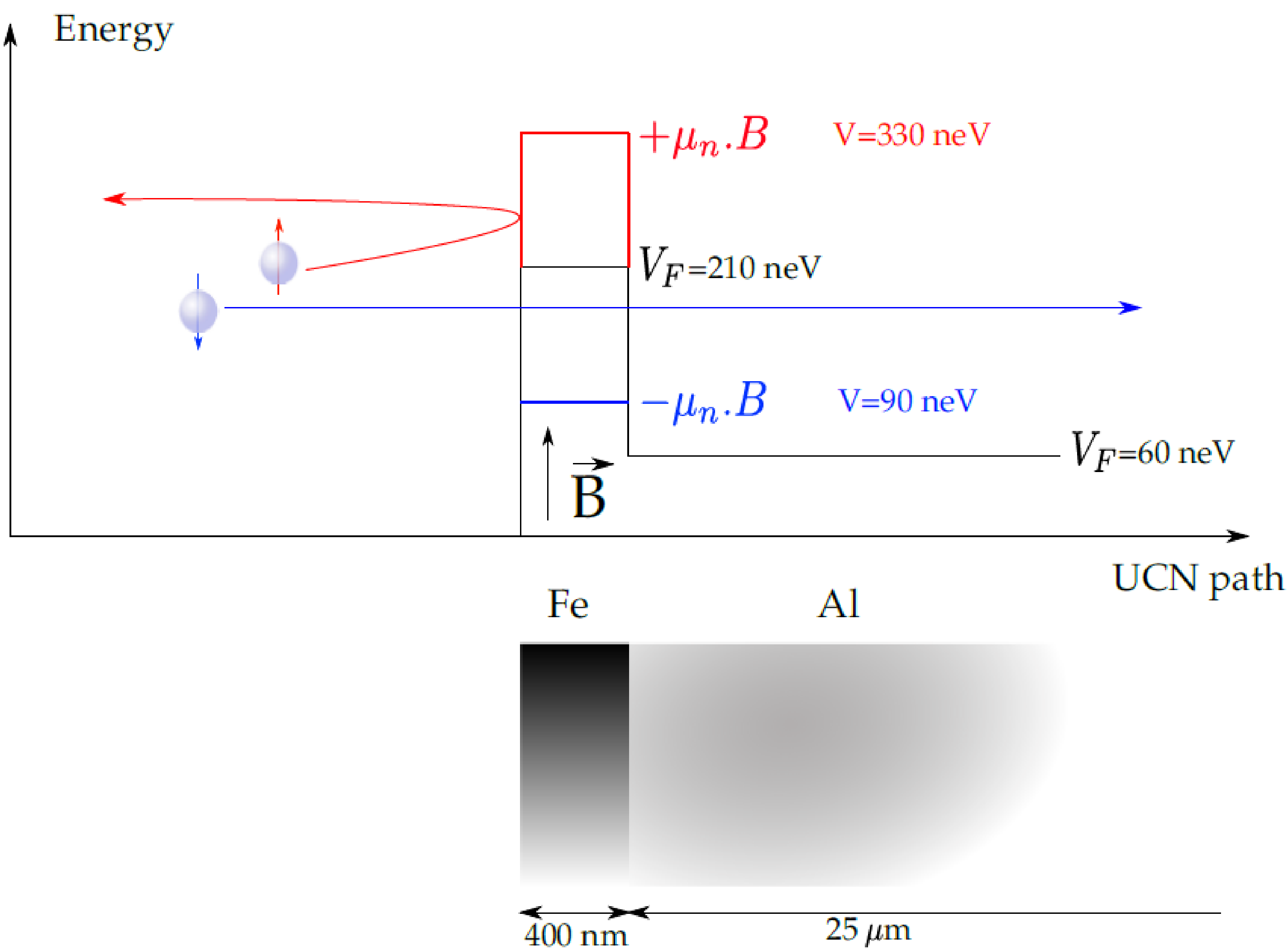
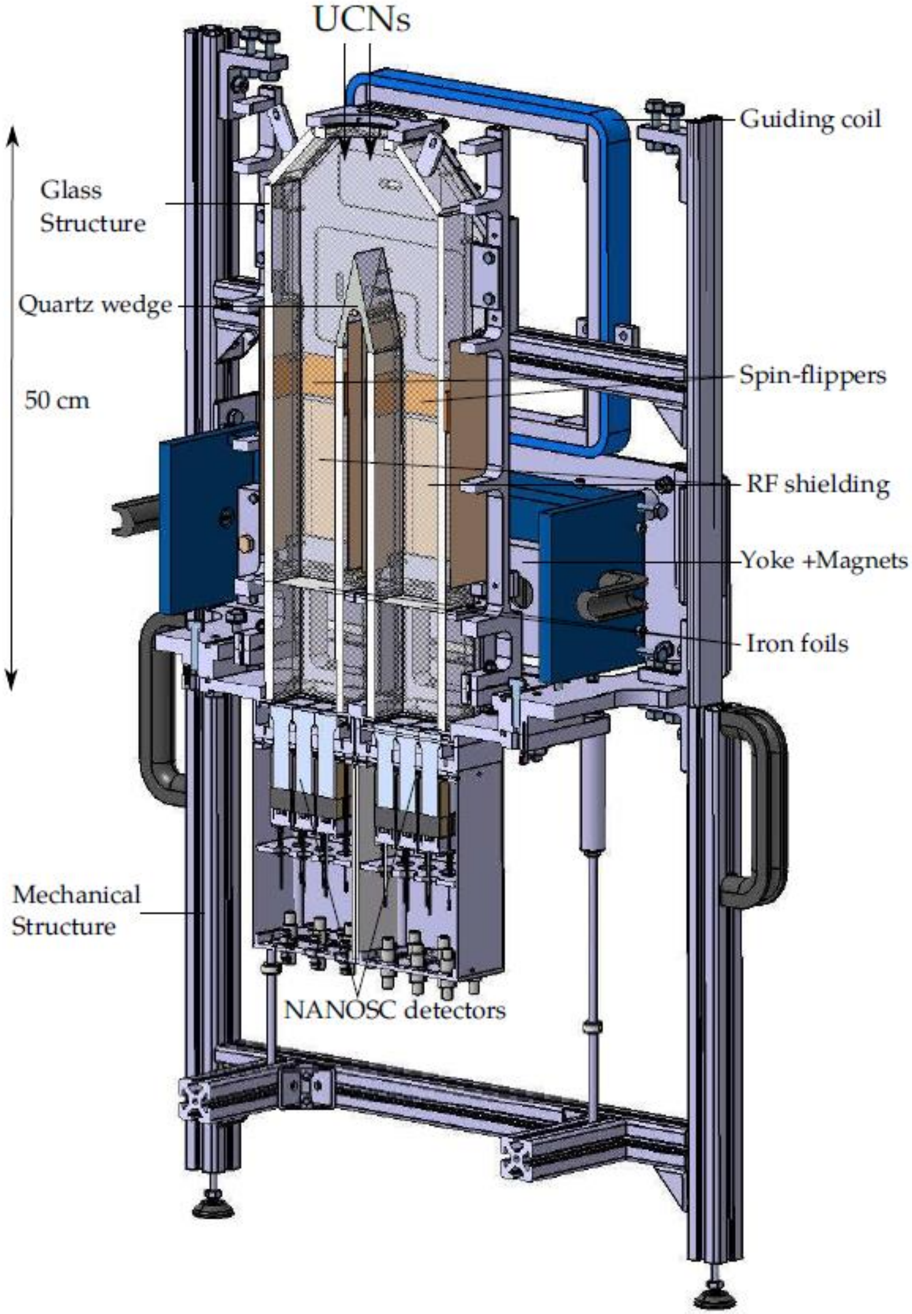
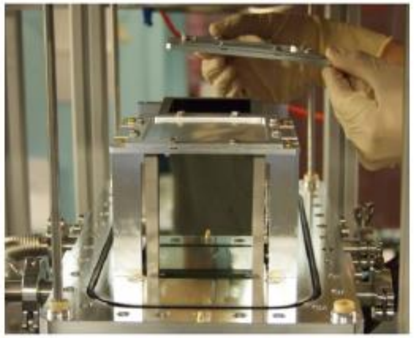
Spin analyser system

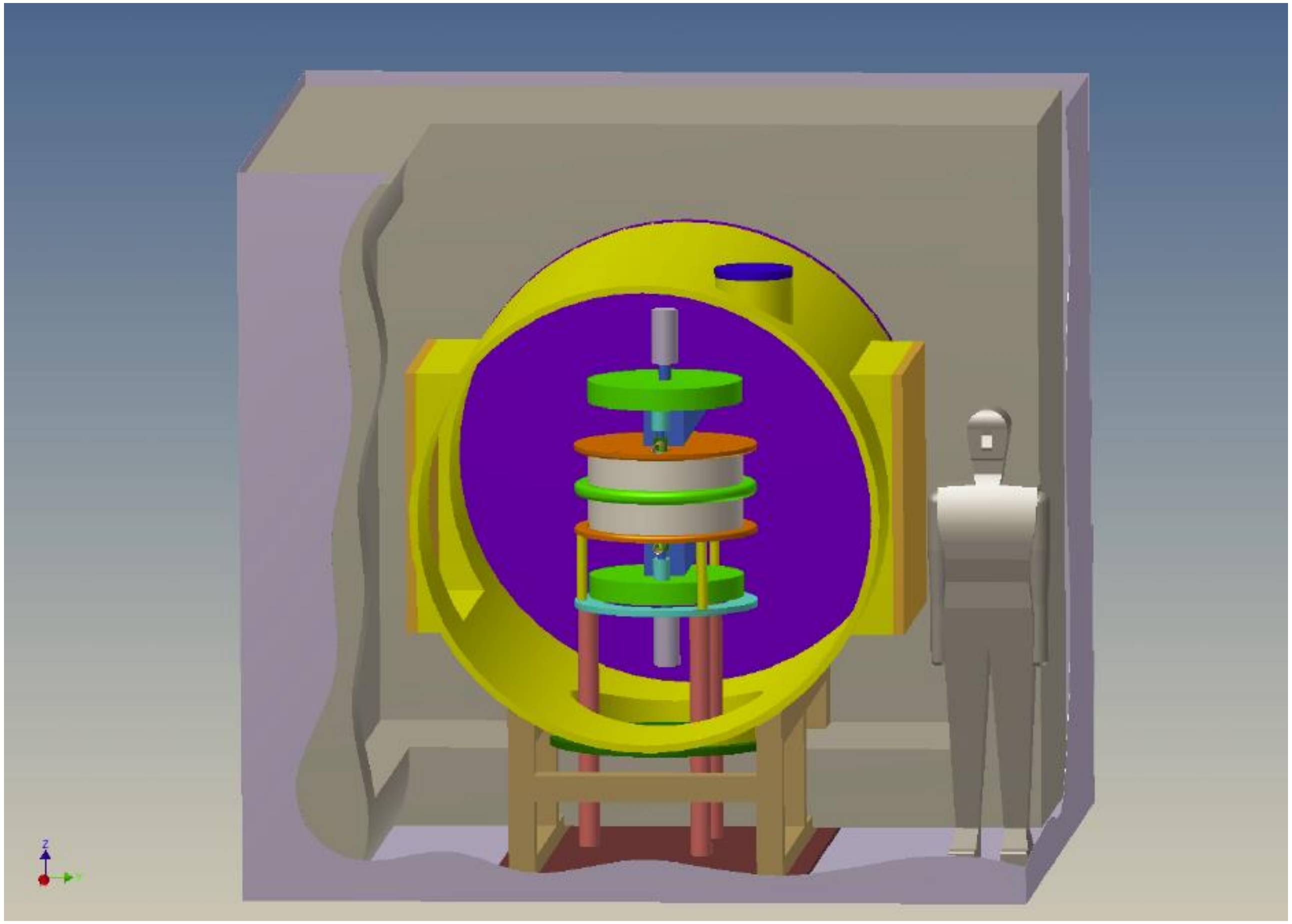



UCNs
Guiding coil
Glass Structure
Quartz wedge
Spin-flippers
50 cm
RF shielding
Yoke +Magnets
Iron foils
Mechanical Structure
NANOSC detectors



USSA

n2EDM



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Current status - Systematic effects

Effects	Goal	Status (Dec. 2012)	Status (Dec. 2013)
Direct Effects			
Uncompensated B-Drifts	0 ± 0.9	2.9 ± 8.6	-0.7 ± 1.1
Leakage Current	0 ± 0.1	0.00 ± 0.05	0.00 ± 0.05
$V \times E$ UCN	0 ± 0.1	0 ± 0.1	0 ± 0.1
Electric Forces	0 ± 0.4	0 ± 0.4	0 ± 0.0
Hg EDM		0.02 ± 0.06	0.02 ± 0.06
Hg Direct Light Shift	0 ± 0.4	0 ± 0.008	0 ± 0.008
Indirect Effects			
Hg Light Shift		0 ± 0.05	0 ± 0.05
Quadrupole Difference	0 ± 0.6	1.3 ± 2.4	1.3 ± 2.4
Dipoles	0 ± 0.5		
At the surface		0 ± 0.4	0 ± 0.4
Other Dipoles		0 ± 3	0 ± 3
Total	0 ± 1.3	4.2 ± 9.4	0.2 ± 4.0

May 2014

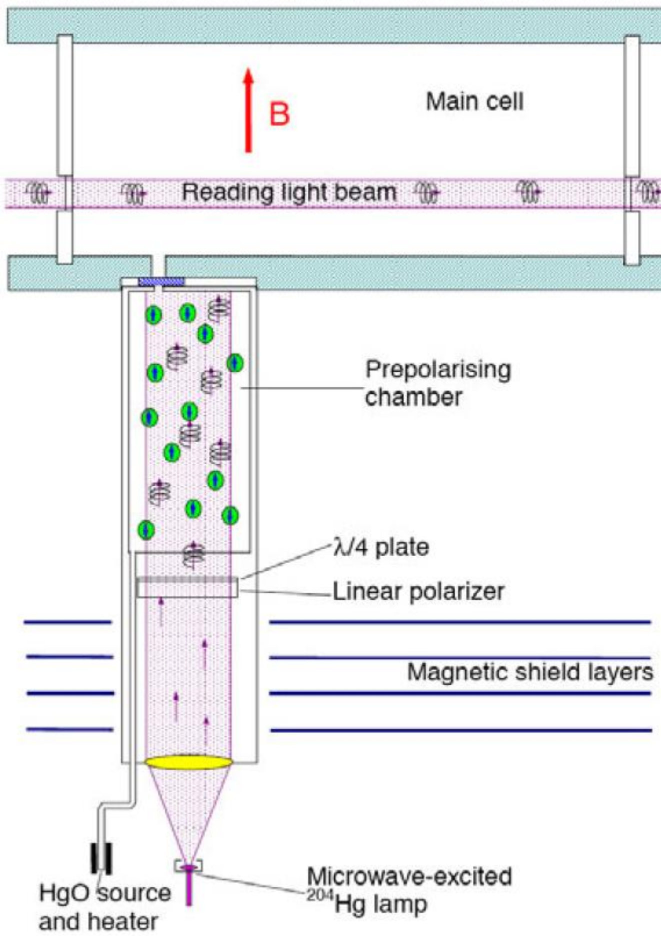
-0.05 ± 0.45

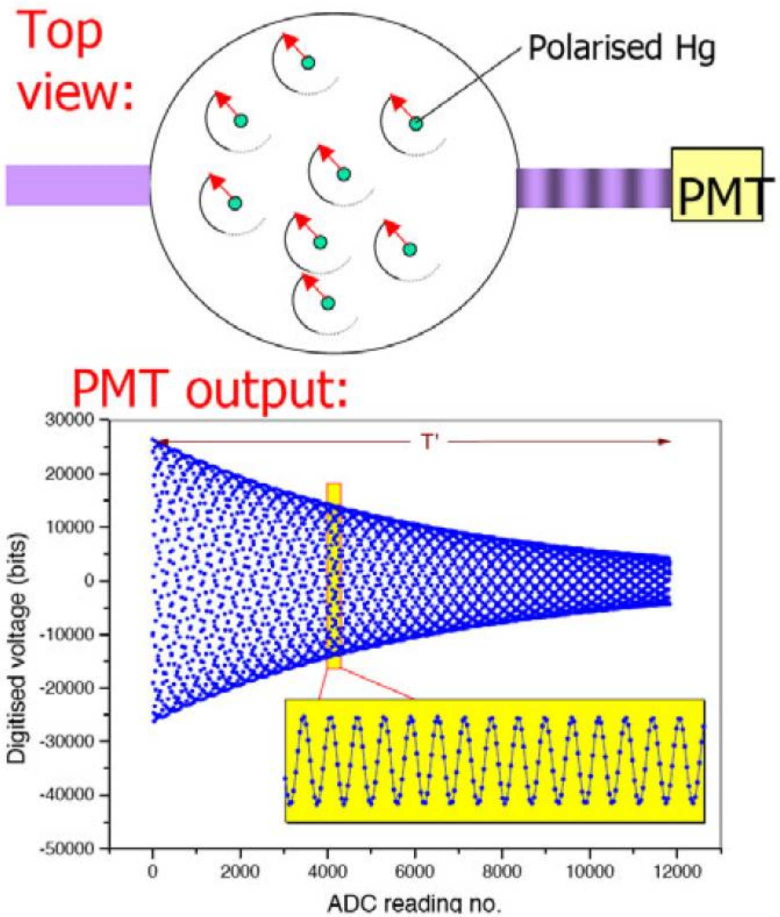
Field mapping & magnetic field stabilization

Fig. 2: Status of the constrain on systematic effects in units of $10^{-27} e \cdot \text{cm}$.

Magnetic field non-homogeneity is the last challenge!

HgM


B
Main cell
Reading light beam
Prepolarising chamber
λ/4 plate
Linear polarizer
Magnetic shield layers
HgO source and heater
Microwave-excited ^{204}Hg lamp


Top view:
Polarised Hg
PMT
PMT output:
T'
Digitised voltage (bits)
ADC reading no.
30000
20000
10000
0
-10000
-20000
-30000
-40000
-50000
0
2000
4000
6000
8000
10000
12000

Geometric phase effect

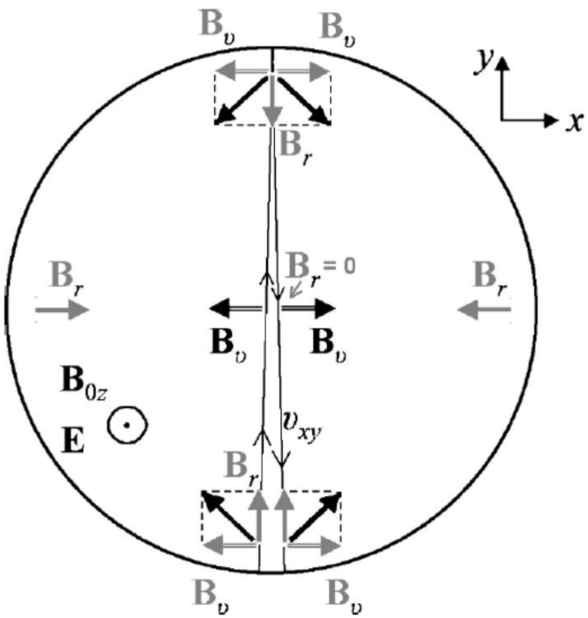
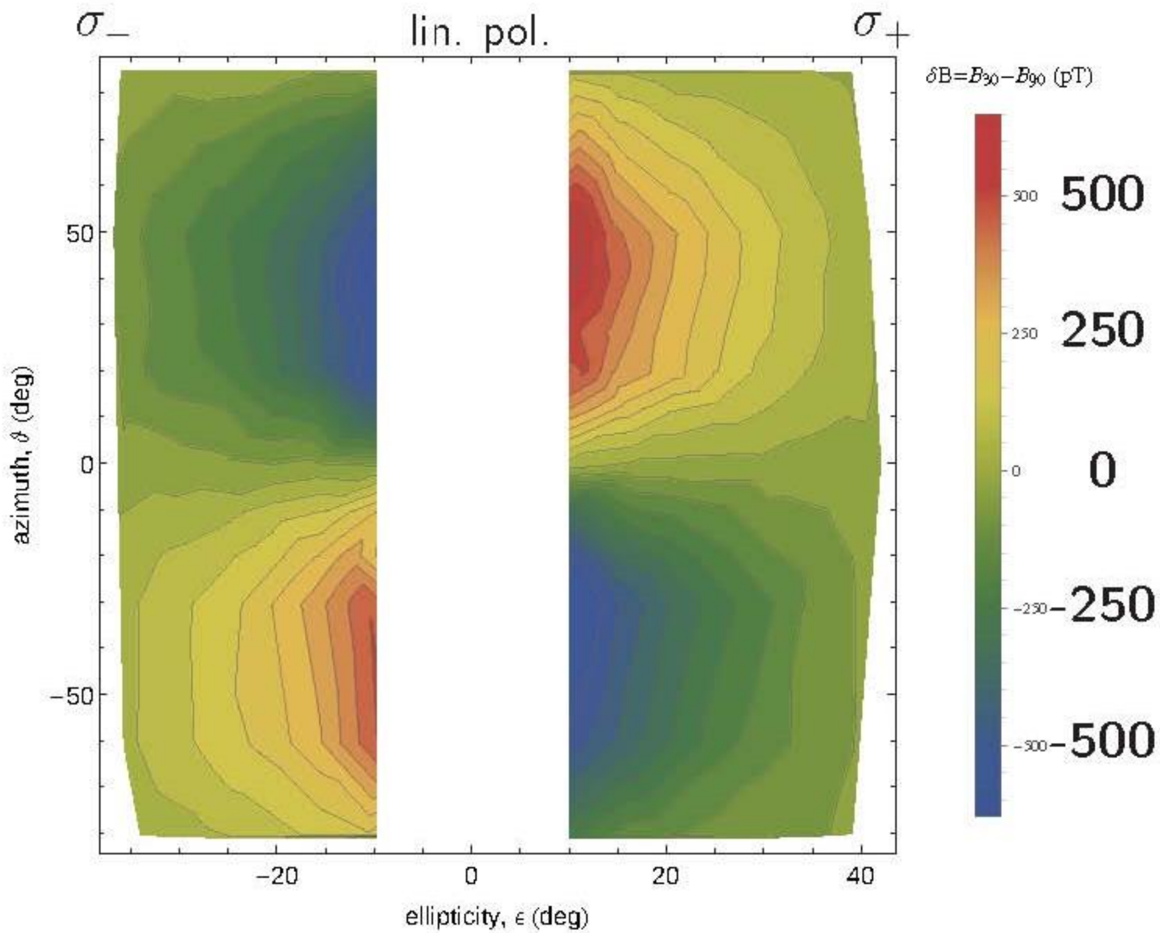
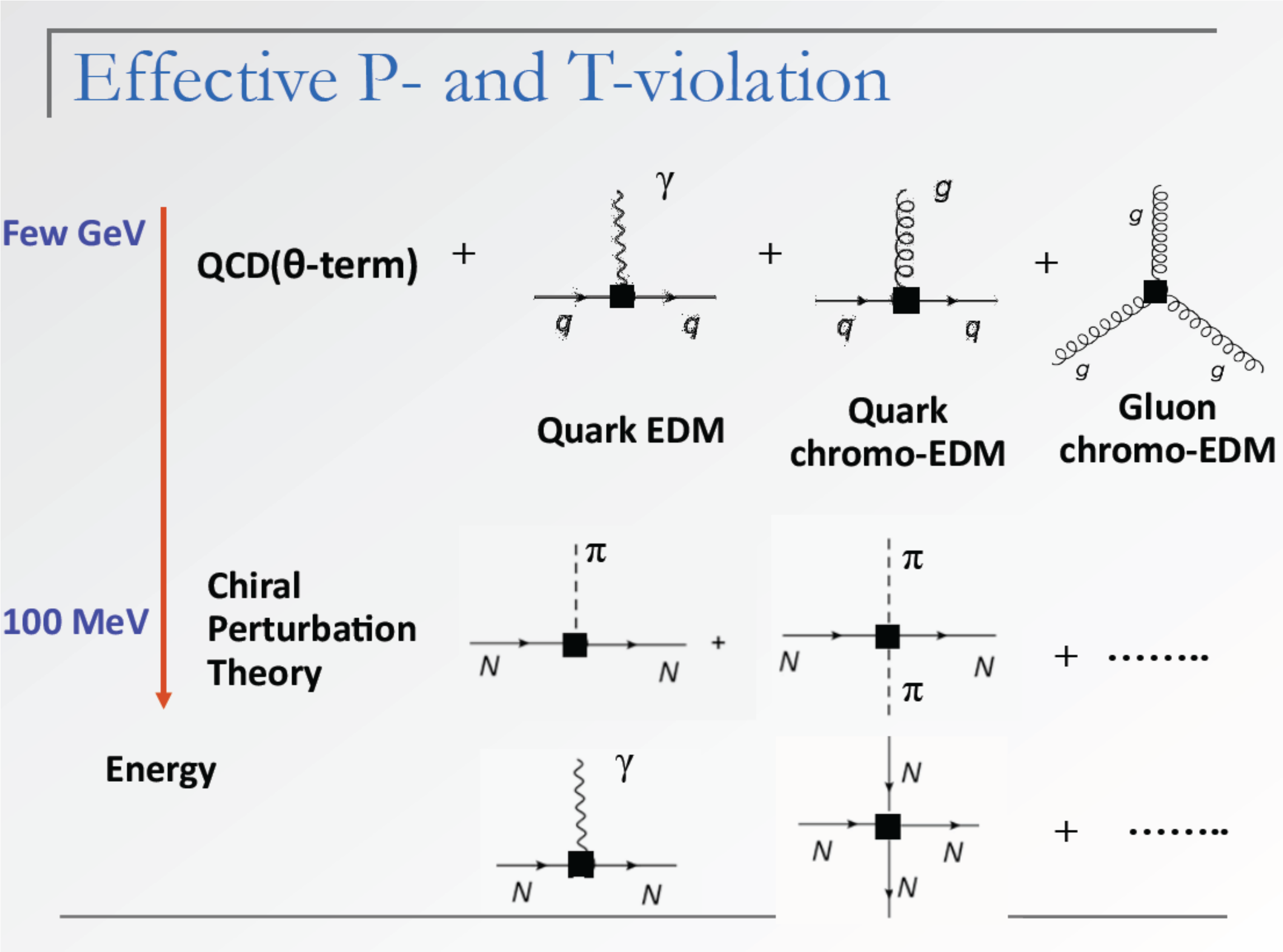


FIG. 5. (Color online) The $\mathbf{B}_{xy}$ fields (in black) seen by a particle going back and forth close to the y axis. Going towards positive y, the $\mathbf{B}_{xy}$ field rotates steadily anticlockwise by about 70° as drawn. The first reflection of the particle towards negative y causes an *instantaneous* anticlockwise rotation by about 110° as drawn. The same two rotations occur on the path to, and at, the second reflection. The size of the rotations depends on the size of B_{0r}/B_υ.

Offset problem



Origins of CP violation



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Origins of CP violation

Conclusions/Summary

- A single hadronic EDM measurement can be fitted by **theta (Standard Model)** or by **new physics**
- At low energies the effects of new physics can be captured by **three effective interactions of dimension-six**
- A deuteron EDM **significantly larger** than nucleon EDM points to new physics (quark chromo-EDM)
- A deuteron MQM is sensitive to the **theta-term**
- Measuring the EDMs of **3He or 3H** (after nucleon+deuteron) is enough to **separate the sources**

JdV, Higa, Liu, Mereghetti, Stetcu, Timmermans, van Kolck, PRC (2011)

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